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A SIMULATION OF THE LUNAR PROSPECTOR'S GAMMA RAY SPECTROMETER

by

Marie C. Grimmer

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Thesis Advisor: David Cleary

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A SIMULATION OF THE LUNAR PROSPECTOR'S GAMMA RAY SPECTROMETER

Marie C. Grimmer
Captain, United States Army
B.S., Embry-Riddle Aeronautical University, 1988

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Author: Marie C. Grimmer

Approved by: David Cleary, Thesis Advisor

Robert E. McMurray, Jr., Co-Advisor

Rudolf Panholzer, Chairman
Space Systems Academic Group

ABSTRACT

The expected response of the Lunar Prospector's Gamma Ray Spectrometer instrument was predicted using a Monte Carlo simulation. The full lunar spectrum was generated using 90 lines and a continuum gamma ray background taken from Apollo 15 and 16 data. The Monte Carlo program uses the exact dimensions and composition of the Gamma Ray Spectrometer in order to most accurately predict spectral performance, assuming an operating temperature on orbit of -30 degrees Celsius. The Gamma Ray Spectrometer will be launched aboard the Lunar Prospector spacecraft on October 24, 1997. The Lunar Prospector will assume a 100 km altitude orbit around the moon, allowing the Gamma Ray Spectrometer to map the elemental composition of the surface. The simulated Gamma Ray Spectrometer response can be used as a comparison for the actual data in order to determine how well the spectrometer is working.

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I. INTRODUCTION

A. OVERVIEW OF THE LUNAR PROSPECTOR PROGRAM

The Lunar Prospector spacecraft is scheduled to be launched October 24, 1997 and will assume a 100 km altitude polar orbit around the moon. The Lunar Prospector's mission is to investigate the moon, including mapping the surface composition, measuring magnetic and gravity fields, and studying volatile release activity. The data collected from the mission will be used to construct detailed maps of surface composition and is needed to improve our understanding of the origin, current state, and resources of the moon.

The Lunar prospector is the first peer reviewed, competitively selected mission in NASA's Discovery Program, which emphasizes "Faster, Better, Cheaper" space exploration. The Lunar Prospector, will demonstrate that high quality science missions can be accomplished economically and on a tight time schedule. Selected on February 28, 1995 for the Discovery program, the Prospector boasts a two-and-a-half year program schedule, with an initial price tag of $51 million (in 1992 dollars). The cost has jumped slightly to $63 million, which includes systems engineering, the spacecraft, science instruments, integration and testing, launch services, launch vehicle, and all mission operations.

The Lunar Prospector is being built by Lockheed Martin Missiles and Space, in Sunnyvale, California, and is headed by Principle Investigator Dr. Alan Binder, who has overall responsibility for the management of the program. Thomas A. Dougherty, also from Lockheed Martin, is the program manager. G. Scott Hubbard, from the NASA Ames Research Center, is the NASA Mission Manager.

B. MISSION

The Lunar Prospector will be launched from Launch Pad 46 at Cape Canaveral, Florida aboard a Lockheed Martin Launch Vehicle-2 on October 24, 1997. A graphic of

the Lunar Prospector's trajectory is shown in Figure 1.1. After firing the Translunar Injection (TLI) stage, the Lunar Prospector will have a 117 hour cruise to the moon.

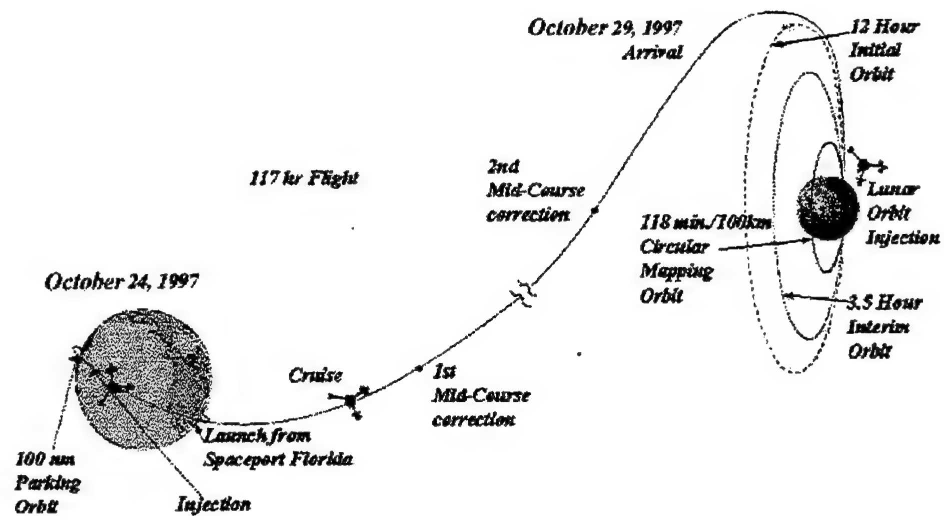

Figure 1.1 The Lunar Prospector's Mission Trajectory (Andolz, 1997)

During this cruise period, ground commands will be sent to the spacecraft to perform two mid-course maneuvers, deploy the booms which carry the science instruments, and collect science instrument calibration data. Once the spacecraft reaches the moon, it will make three separate lunar orbit insertion burns. The first insertion burn will place the spacecraft in a 12 hour, elliptical orbit. The next boost, scheduled 24 hours later, will speed the spacecraft to a 3.5 hour elliptical orbit. A final burn, the next day, will put the spacecraft in a circular 118 minute, 100 km (62 mile) altitude, polar mapping orbit. After Lunar Prospector assumes this nominal orbit it will begin a one year mapping mission and periodic maintenance maneuvers will be made to keep the spacecraft in its proper orbit.

The spacecraft is expected to exceed its one-year design and, if fuel is available, will continue its mapping mission. The Lunar Prospector may continue mapping from elliptical orbits whose low points are only 10 km above the surface. The mission will

cease when the fuel for orbit maintenance runs out and the spacecraft impacts the lunar surface.

C. THE SPACECRAFT

The spacecraft structure is triangular in shape and is made of graphite epoxy. The structure is covered with rounded solar panels, giving the spacecraft the cylindrical appearance depicted in Figure 1.2 below. It measures 1.37 meters (4.5 feet) in diameter and 1.29 meters (4.25 feet) high. The science instruments will be deployed on three symmetric radial booms which extend 2.5 meters (8.2 feet) from the spacecraft, which is illustrated in the right-hand drawing of Figure 1.2 below.

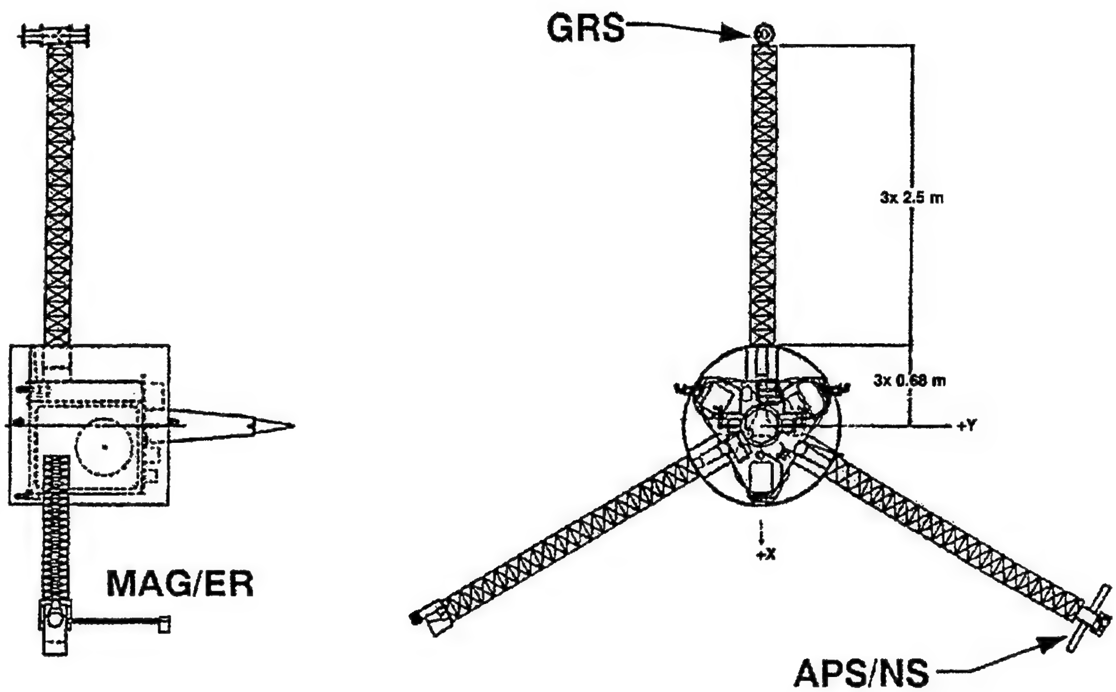

Figure 1.2 Lunar Prospector in the Deployed Configuration (Lockheed, 1996)

The spacecraft will use spin-stabilization provided by six hydrazine monopropellant 22-Newton thrusters capable of providing a maximum velocity change of 1430 meter per second. These thrusters will provide all the attitude control necessary and consume 138 kg (303 lb.) of high purity hydrazine during the entire mission. The propulsion system is part of the basic spacecraft structure, employing a simple blowdown system which uses titanium tanks and 304L plumbing, with flight proven transition joints and thrusters (Andolz, 1997).

The power system consists of body-mounted solar cells and a rechargeable battery. The subsystem has no high voltage capability and the highest voltages available during ground operations are 35 Volts from the battery and 40 Volts from the illuminated array. The Lunar Prospector solar array will deliver about 230 Watts on orbit which is more than sufficient to provide the 200 Watts needed to run the electrical equipment. During eclipse periods the spacecraft will be powered by a small 5.9 kg (13 lb.) battery. The battery consists of 22 prismatic nickel-cadmium cells and has an energy storage capacity of 5 Ampere-hours. During periods of sunlight, the solar cells provide enough power to recharge the battery. The spacecraft uses a single point ground philosophy and all power is returned through the harness, not through the structure. All components are electrically bonded to the structure ground by metallic ground plate or wire attachment.

The spacecraft will have no on-board computer and ground command will be conducted via a 3.6 kbps telemetry link. The Command and Data Handling (C&DH) Electronics unit receives uplinked commands from the spacecraft's S-band transponder on the uplink frequency of 2093.0541 MHz. The C&DH sends commands to the science instruments, controls the solar arrays and power distribution, and receives data from the science instruments. The C&DH downlinks this data, as well as sensor and actuator information, at 2273.000 MHz to ground control. The spacecraft has a phased-array medium gain antenna and an omnidirectional low gain antenna. The antennae are shown protruding out of the right side of the left-hand drawing in Figure 1.2. The medium gain antenna is mounted to the spacecraft and the omnidirectional antenna is mounted on top of it.

D. SCIENCE INSTRUMENTS AND EXPERIMENTS

The Gamma Ray Spectrometer is one of six instruments chosen as the science payload aboard the Lunar Prospector. The experiments were selected from a long list of proposals based on their scientific value, compatibility with a simple, spin-stabilized spacecraft, and for low weight, low power, and minimal data rate requirements. The science instruments are mounted on three deployable masts and are located external to the spacecraft body after launch. The Gamma Ray Spectrometer will be discussed in detail in Chapter III and the other five experiments selected are mentioned below:

1. Neutron Spectrometer

The Neutron Spectrometer, along with the Gamma Ray Spectrometer, will return global maps on lunar elemental composition, which will be used to understand the evolution of the lunarhighland crust, the duration and extent of ballistic volcanism, and to identify lunar resources. One of the most interesting missions the Neutron Spectrometer will perform is to locate any significant quantities of water ice in the cold areas of the lunar surface. The media's coverage of Clementine's findings, suggesting the possibility of existing ice, has heightened interest in Lunar Prospector, and the Neutron Spectrometer in particular.

The Lunar Prospector's Neutron Spectrometer has a water detectability limit of better than 0.01%, which means it could sense as little as a cup of water in a cubic yard of lunar soil (Andolz, 1997). With Lunar Prospector's polar coverage and the sensitivity of this instrument, this mission will finally and definitely, confirm or deny, the existence of ice on the moon. The discovery of ice on the moon would have a significant impact on space exploration , as it would provide water for life support, and a source of oxygen and hydrogen needed to produce rocket fuel.

2. Alpha Particle Spectrometer

The Alpha Particle Spectrometer will monitor outgassing events on the lunar surface by detecting alpha particles from the radon gas and its decay product, polonium (Andolz, 1997). This will help scientists determine if this is a possible source for the very thin lunar atmosphere. Attempts will also be made to correlate outgassing events with crater age. The Lunar Prospector's alpha particle experiment is an advanced version of the instrument flown on the Apollo 15 and 16 missions. Until Apollo, the moon was thought to be tectonically (causing deformation in the lunar crust) and volcanically dead (Andolz, 1997). As a result of the Apollo missions, scientists now are aware that the moon is active, though much less active than Earth or Mars. The Lunar Prospector's Alpha Particle Spectrometer will be sensitive enough to detect any activity.

3. Magnetometer and Electron Reflectometer

The Magnetometer and the Electron Reflectometer will work together to provide a map of the lunar magnetic fields, and thus are described together in this section. The moon does not have a magnetic field like the earth, but has various regions that have magnetic fields. Mapping these regions can provide scientists with insight on whether they originated from a global magnetic field, like the earth, or from meteoroid impact, or some other source. The data from these instruments will also provide insight into the composition of the lunar core. Magnetic mapping can also be used to locate ore and areas rich for possible future mining operations.

4. The Doppler Gravity Experiment

The Doppler Gravity Experiment will provide a map of the lunar gravity field. The data from the Apollo missions are incomplete and a complete map of lunar gravity is necessary for future unmanned and manned missions. The experiment will use Doppler tracking of S-band radio signals to determine the gravity field and characterize the

spacecraft orbit (Andolz, 1997). It will provide scientists with information on density differences in the crust, the internal density of the moon, and the nature of the core.

II. FUNDAMENTALS OF GAMMA RAY RADIATION DETECTION

A. GAMMA RAYS

Gamma rays are highly penetrating, electromagnetic radiation (photons) emitted by radioactive decay or produced during cosmic ray collisions. They have an extremely small wavelength which, according to Planck's Law (energy equals Planck's constant times the speed of light divided by wavelength) means they are extremely energetic quanta of light. Gamma rays are defined by Webster as "having an energy greater than several hundred thousand electron volts". These energy ranges overlap with x-rays , so it is often more meaningful to distinguish gamma rays on the basis of where they originate. Gamma rays are the radiations originating within the nucleus, while x-rays originate in the electron cloud surrounding the nucleus.

B. RADIATION INTERACTIONS

The operation of any radiation detector depends on the manner in which the radiation to be detected interacts (loses its energy in matter) with the material of the detector itself. Therefore, to understand how a detector works, one must have a familiarity with the basic ways radiation interacts. There are three types of interactions for gamma rays which play an important role in radiation measurement: photoelectric absorption, Compton scattering, and pair production. All three of these interactions lead to the partial or complete transfer of gamma ray photon energy to electron energy.

In photoelectric absorption, an incoming gamma ray photon interacts with an absorber atom and completely disappears. An energetic photoelectron is ejected by the atom from one of its bound shells. Photoelectric absorption is the predominant interaction for gamma rays of relatively low energy. Compton scattering occurs during the interaction between the incident gamma ray photon and an electron in the absorbing material. The incident photon transfers a portion of its energy to the electron, which becomes a recoil electron. The probability of Compton scattering per atom of the

absorber depends on the number of electrons available as scattering targets (increasing linearly with Z, the atomic number of the absorber). This is the predominant interaction mechanism for gamma rays energies typical of radioisotope sources. In pair production, the gamma ray photon disappears and is replaced by an electron-positron pair. Pair production is predominantly confined to high energy gamma rays and is energetically possible only if the gamma ray energy exceeds twice the rest mass energy of an electron (2 x 0.511 MeV or 1.022 MeV). The excess energy above 1.022 MeV is shared by the electron and positron. Two annihilation photons, each 0.511 MeV, are normally produced as the positron annihilates an electron in the absorbing medium. This annihilation radiation has a significant effect on the response of gamma ray detectors. Figure 2.1 below shows the relative importance of the three major gamma ray interactions at various energies as a function of the absorber atomic number. The curve on the left represents the energy at which the probability of photoelectric absorption (tau) and Compton scattering (sigma) are equal. The curve on the right represents the energy at which Compton scattering and pair production (kappa) are equally probable.

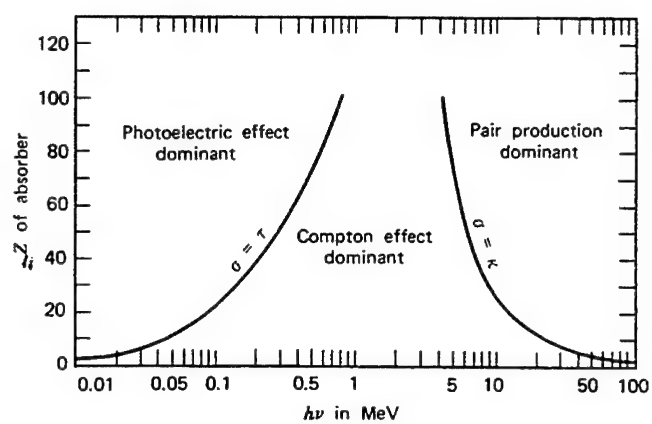

Figure 2.1 Three areas of Z value vs. energy where photoelectric absorption, Compton scattering, and pair production each predominate. (Evans, 1955)

C. GENERAL RADIATION DETECTION TERMINOLOGY

Radiation detectors can be operated in the current mode or the pulse mode. Pulse mode offers higher sensitivity because it can detect discrete pulses and is the mode used in gamma ray radiation detection. In pulse mode output is recorded for each individual quantum of radiation that interacts with the detector. The output of a pulse mode detector normally consists of a string of individual signal pulses, each representing the interaction of a single quantum of radiation within the detector. The amplitude of each of these signal pulses carries information regarding the charge generated by that particular interaction in the detector. The most common way of displaying pulse amplitude information is by differential pulse height distribution. This is the differential number dN of pulses observed with an amplitude within the differential amplitude increment dH, divided by that increment, or dN/dH (Knoll, 1979). Pulse amplitude information is also displayed as dN/dE and, since H and E are proportional, can be used interchangeably.

In gamma ray radiation spectroscopy the object is to measure the energy distribution of the incident radiation. One way to evaluate the resolution of a detector is by noting its response to a single energy source. This is called the response function and Figure 2.2 illustrates examples of detectors with relatively good and relatively poor resolution. H indicates pulse height and H_0 is the average pulse height point.

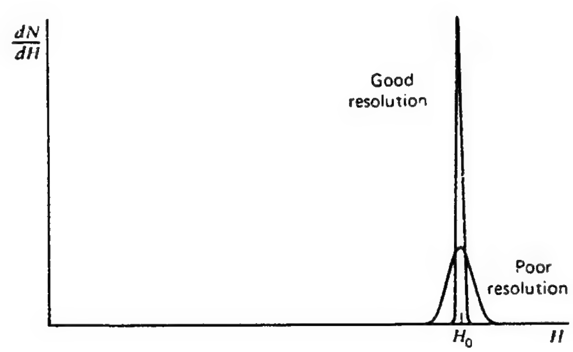

Figure 2.2 The response functions for two hypothetical detectors with relatively good and relatively poor resolution. (Knoll, 1979)

The formal definition of energy resolution is best depicted by Knoll (1979) in Figure 2.3. The differential pulse height distribution is shown for a hypothetical detector and depicts only the radiation of a single energy. Full width half maximum (FWHM) is the width of the distribution at a level which is just half the maximum ordinate of the peak. The energy resolution of a detector is the FWHM divided by the location of the peak centroid, H_0. Energy resolution, R, is a dimensionless fraction normally expressed as a percentage (Knoll, 1979).

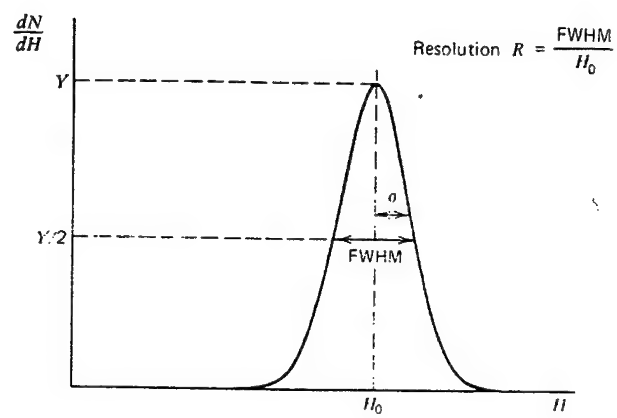

Figure 2.3 The definition of detector resolution. (Knoll, 1979)

Another term frequently used when evaluating radiation measuring devices is called detection efficiency. This figure is simply the number of pulses counted to the number of photons that entered the detector.

D. COMPONENTS OF A GAMMA RAY SPECTROMETER

1. Scintillators

The materials used to detect gamma rays are called scintillators. Radiation is detected by the scintillation light produced in certain materials. Scintillation is the conversion of the energy of a photon to multiple visible light photons. Scintillation is also defined by Webster as, "a flash of light produced in certain media by absorption of an ionizing particle or photon. In all three interactions listed in Section II , B energetic electrons are produced. This is what produces the scintillation light in the gamma ray detector. The more energetic the electron, the more light produced. The discovery of the inorganic scintillator thallium-activated sodium iodide, NaI (T1), in the early 1950s began the study of gamma ray scintillation spectroscopy (Knoll, 1979).

2. Photomultiplier tubes

A photomultiplier tube converts scintillated light into electrical pulses. The brighter the light pulse, the higher the energy of the gamma ray. The two major elements of the photomultiplier tube are the photocathode and the electron multiplier structure, both depicted in Figure 2.4.

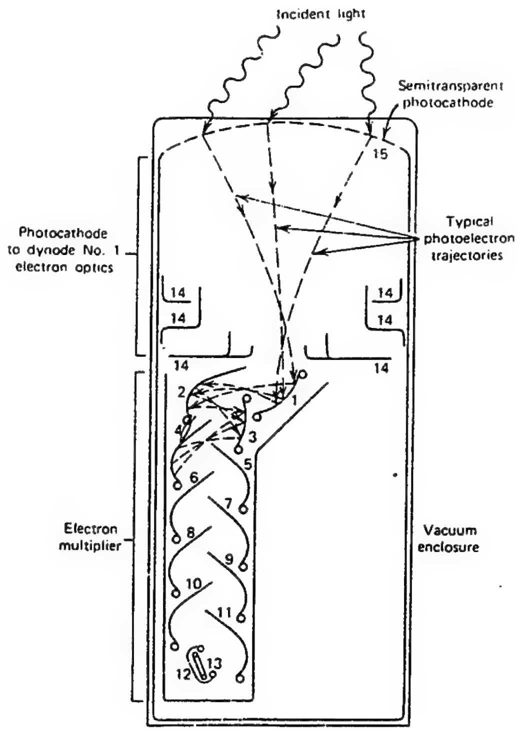

Figure 2.4 The basic components of a photomultiplier tube. (Knoll, 1979)

The photocathode converts as many of the incoming visible light scintillation photons as possible into low energy electrons. The photoelectrons produced will be a pulse of similar duration to the scintillator pulse. The electron multiplier provides an efficient collection mechanism for the photoelectrons and then employs a multiple stage amplifier. The amplifier will create 10^7 to 10^{10} electrons from a single scintillation pulse. The total charge is then collected at the anode or output stage (shown as number 13 in Figure 2.4) of the photomultiplier structure.

3. Multichannel Analyzer

The function of the multichannel analyzer is to convert an analog signal (ie. the pulse amplitude from the photomultiplier tube) to an equivalent digital number. Once the signal is converted to digital it can be stored and displayed by means of computer. The multichannel analyzer is made up of a pulse height track-and-hold module and an analog-to-digital converter (ADC). The pulse height track-and-hold module records the electrical pulses from the photomultiplier tube and the ADC derives a digital number that is proportional to the amplitude of the pulse presented at its input. The ADC is a key component of the multichannel analyzer and has a big impact on its overall performance. The output from the ADC is stored in memory banks which are subdivided into different addressable locations. The number of locations corresponds to the maximum number of channels available in the analyzer. The number of memory locations is normally made by a power of two, with capacities between 256-4096 channels. The contents of the memory can be displayed in a number of ways. Commonly, they are displayed on a cathode ray tube (CRT) which shows the contents of the channel (counts) on the y-axis and the channel number (channel) along the x-axis. This provides a graphical representation of the pulse height spectrum discussed above. Basically, the multichannel analyzer generates a histogram by summing counts in each of the memory locations.

4. Summary of Spectrometer Components

A gamma ray enters a detector and produces a flash of light when it interacts with the scintillator. The light created by the scintillator is then converted into electrical pulses and amplified in the photomultiplier tube. The multichannel analyzer converts the pulse amplitude to a digital signal. The digital information is stored in separate registers that correspond to the number of channels in the analyzer. The output can then be displayed in the form of a pulse height spectrum depicting counts vs. channel.

E. RADIATION SPECTROSCOPY WITH SCINTILLATORS

As mentioned in Section II, B, there are three interaction mechanisms important in gamma ray spectroscopy: photoelectric absorption, Compton scattering, and pair production. As Figure 2.1 depicts, the atomic number of a medium has a strong influence on the relative probabilities of these three interactions. Photoelectric absorption is the preferred mode for gamma ray scintillators, so detector materials made of elements with a high atomic numbers are used.

1. Photoelectric Absorption

In photoelectric absorption the gamma ray photon disappears and a single high energy photoelectron is produced in its place. The photoelectron is produced from one of the electron shells of the absorber atom. Its kinetic energy (E_{e-}), as depicted in Figure 2.5, is the incident photon energy *hv*, minus the binding energy of the electron in its original shell (E_b), which is recovered in an x-ray emission from another electron dropping in. Typical binding energies are only a few keV, so they are normally disregarded.

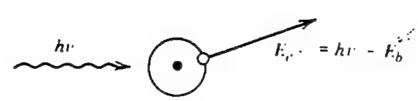

Figure 2.5 The photoelectric absorption interaction process. (Knoll, 1979)

The liberated photoelectron carries off most of the gamma ray energy, making photoelectric absorption an excellent way to measure the energy of the original gamma ray. The total electron kinetic energy, plus the x-ray energy, equals the incident gamma ray energy. For a monoenergetic gamma ray source, the differential distribution of electron kinetic energy for a series of photoelectric absorption events would be a simple

delta function. This is depicted in Figure 2.6. Recall dN/dE is the differential number of pulses per differential pulse energy. The single peak appears at the same total electron energy as the incident gamma ray.

Figure 2.6 The differential distribution of electron kinetic energy for a series of photoelectric absorption events. (Knoll, 1979)

2. Compton Scattering

Compton scattering is the creation of a recoil electron and scattered gamma ray photon with the division of energy between them dependent on scattering angle. A sketch of the interaction is given in Figure 2.7.

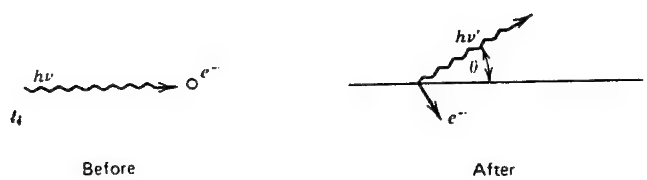

Figure 2.7 A Compton scattering interaction. (Knoll, 1979)

Two extreme cases can be identified. The first is a grazing angle scattering, where theta is approximately equal to zero. In this extreme, the recoil Compton electron has very little energy and the scattered gamma ray has nearly the same energy as the incident gamma ray. The other extreme is a head-on collision in which theta equals pi, or 180 degrees. In this case, the incident gamma ray is backscattered from its original direction and the electron recoils in the direction of incidence. In this circumstance the

maximum energy possible in a single Compton interaction will be transferred to the electron. In normal circumstances, all scattering angles will occur in a detector resulting in a continuum of energies transferred to the electron. For any one specific gamma ray energy, the electron energy distribution, due to single Compton scattering, will be similar to that depicted in Figure 2.8. Most often we will see multiple Compton scatterings followed by photoelectric absorption or pair production. Either of these will produce a full energy peak.

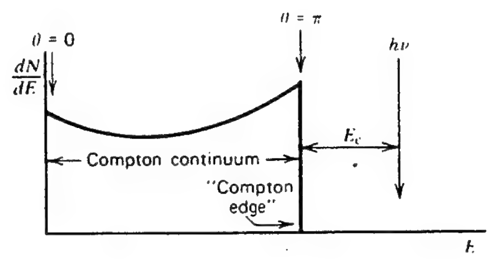

Figure 2.8 General shape of the Compton continuum. (Knoll, 1979)

3. **Pair Production**

In pair production, an electron-positron pair is created at the point of complete disappearance of the photoelectron. A minimum energy of twice the rest mass energy of the electron ($2m_0c^2 = 2 \times 0.511$ MeV or 1.02 MeV), is required to create the electron-positron pair. Any energy that exceeds this value is converted to kinetic energy shared by the electron and positron. For typical energies, the electrons and positrons travel only a few millimeters through the absorbing medium before losing all their energy. When a positron annihilates two 0.511 MeV photons are created. One, both, or neither may get absorbed by the detector. If neither escape the detector a full energy peak will be produced at the incident gamma ray energy. If one leaves the detector a single escape peak will appear at 0.511 MeV below the incident gamma ray energy. If both escape the detector a double escape peak is created at 2.011 MeV below the original gamma ray energy.

4. Effects of Surrounding Materials

In any practical application, the scintillator will be surrounded by various other materials which can have a large impact on the detector's response. The only way to shield a detector from cosmic rays is a massive amount of shielding. For applications on spacecraft this requirement can be eliminated by the use of an anticoincidence shield. The primary detector is surrounded by a second detector or shield, and the output of the primary detector is only accepted if there is not a coincidental pulse in the shield. If there is complete absorption of the radiation source within the primary detector then that pulse will be accepted. However, the cosmic radiations will often interact in both detectors, and can be eliminated from the output of the primary detector through the use of the anticoincidence shield. Another benefit of the anticoincidence shield is that it will minimize the Compton continuum in the recorded spectrum, because a Compton scattered gamma ray from the primary detector will quite likely interact with the anticoincidence shield as well. The influence of the surrounding materials on a detector's response is illustrated in Figure 2.9.

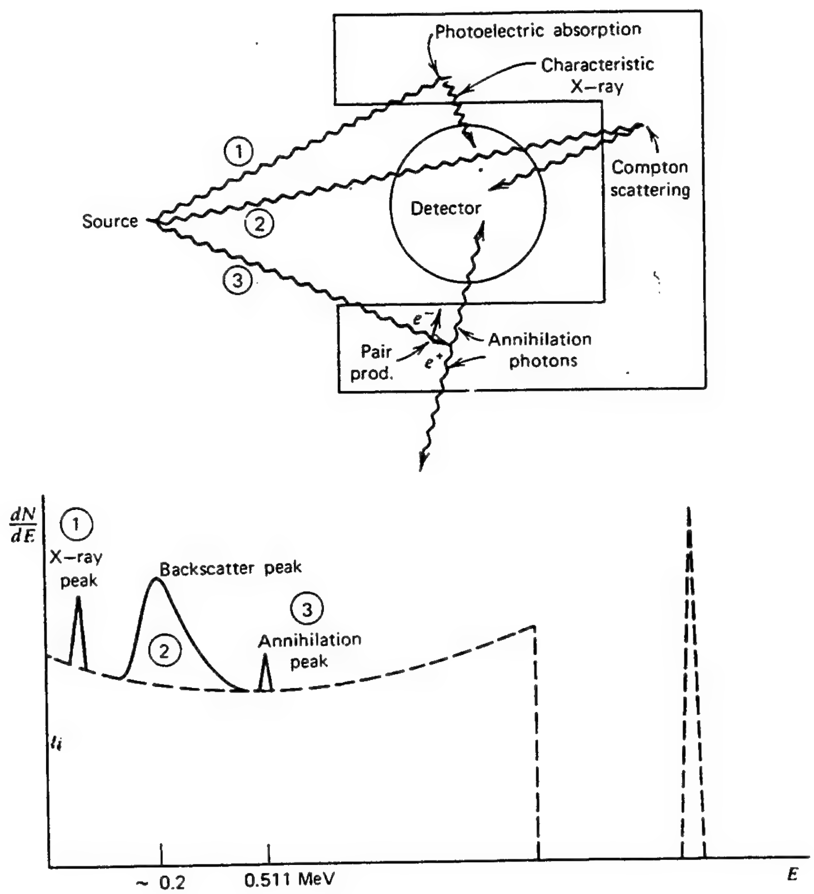

Figure 2.9 Influence of surrounding materials on detector response. (Knoll, 1979)

III. LUNAR PROSPECTOR'S GAMMA RAY SPECTROMETER

A. MISSION OBJECTIVES

The fundamental purpose of the Lunar Prospector's Gamma Ray Spectrometer experiment is to provide global maps of the elemental composition of the lunar surface. The elements mapped will be potassium, thorium, uranium, iron, silicon, magnesium, aluminum, oxygen, calcium, and titanium. The Gamma Ray Spectrometer will detect the naturally radioactive elements potassium, thorium, and uranium by their gamma rays and those of their decay chain products. The remaining elements are detected by gamma rays produced during cosmic ray interactions. Knowledge of the concentrations and locations of these elements will help scientists determine the composition and evolution of the lunar crust. Potassium, thorium, and uranium will be used to help map the location of KREEP (potassium [K], rare earth elements [REE], and phosphorus [P]). KREEP is believed to have developed late in the formation of the crust and upper mantle and will be an important tool in determining lunar evolution.

B. DETECTOR COMPONENTS

1. The Scintillator

The Lunar Prospector's Gamma Ray Spectrometer is a more advanced model than the version flown on the Apollo missions. The spectrometers flown on these missions used scintillator detectors made of NaI(T1). Since that time much progress has been made with solid-state detectors of silicon and high purity germanium. Because of the poor resolution of the early NaI(T1) detectors, only a few gamma ray lines were observable in the Apollo lunar spectra. Since the Apollo missions, scientists have calculated the expected fluxes for less intense gamma rays. These calculated fluxes were

then used to predict the findings of more sensitive detectors which can distinguish between gamma ray lines only a few KeV in energy apart (Reedy, 1978). The Lunar Prospector will use a scintillator made of Bismuth Germanate or BGO. This material, $Bi_4Ge_3O_{12}$, is used because the high Z-value (83) of bismuth leads to a high photoelectric cross section for gamma rays (Knoll, 1979). The Lunar Prospector data set is expected to be 2.5 to 8 times better in terms of peak intensity than the NaI data from the Apollo orbiters. This is primarily due to the high-Z BGO used in the Lunar Prospector's Gamma Ray Spectrometer. The Lunar Prospector's scintillator is a solid cylinder of BGO which measures 7.11 cm in diameter x 7.62 cm in height.

2. The Photomultiplier Tube and Anticoincidence Shield

The Lunar Prospector's scintillator will be attached to a photomultiplier tube similar to the one described in Chapter II. Surrounding the BGO is an anticoincidence shield made of BC454, a borated plastic manufactured by the company Bicron. The dimensions of the anticoincidence shield are 11.8 cm in diameter x 20.0 cm in height with a well cored out for the BGO detector. The anticoincidence shield is attached to a separate photomultiplier tube as illustrated in Figure 3.1. The scintillator and the anticoincidence shield are wrapped separately in a reflective Teflon foil, including the area in between them, to ensure that only light from that region is sensed by the attached photomultiplier tube.

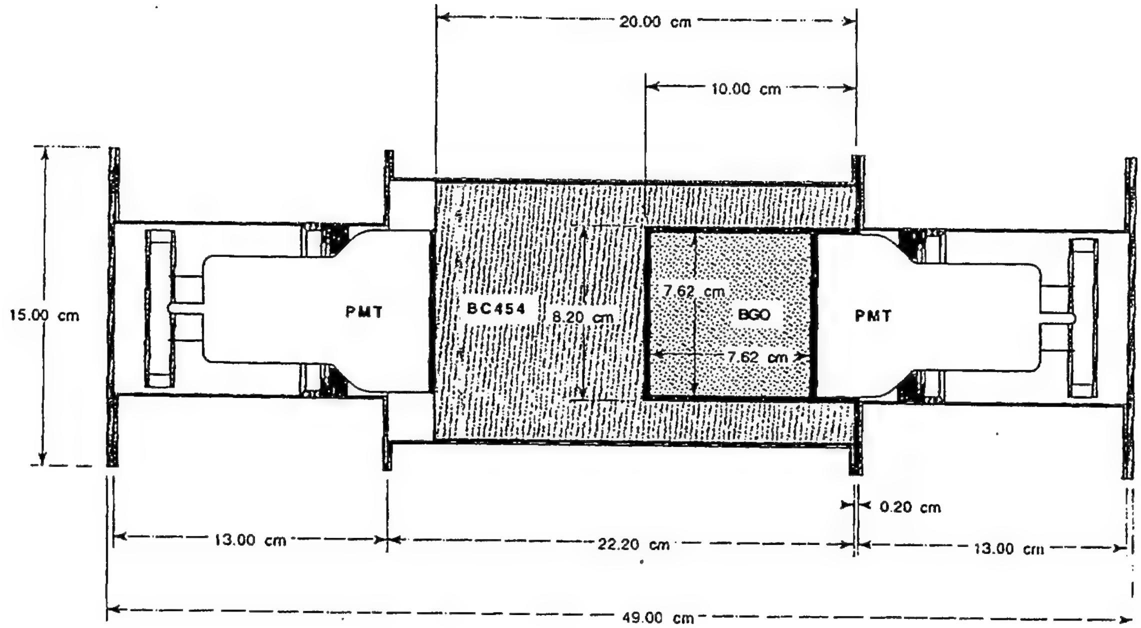

Figure 3.1 A schematic of the Lunar Prospector's Gamma Ray Spectrometer (Lockheed, 1996)

The scintillator, photomultiplier tubes, and anticoincidence shield are mounted on one of the three telescoping booms which will keep the detector away from the main structure of the satellite.

3. Spectrometer Electronics Subsystem

The detector on the boom is connected via wire to the SES (Spectrometer Electronics Subsystem) located on top of the satellite's main body. The SES provides the electronics interface components for the Gamma Ray Spectrometer, the Neutron Spectrometer, and the Alpha Particle Spectrometer. The SES contains the pulse-height track-and-hold module and the analog-to-digital converter, which essentially make up a multichannel analyzer. The detector will measure gamma rays in the 0.1 to 9 MeV range and SES will provide 512 channels. The data from the SES will be sent to the Lunar Prospector's Command and Data Handling Electronics Unit and then transmitted to

ground control where it can be passed to scientists. The SES weighs 7.0 kg and measures 23.0 x 19.2 x 15.9 cm, with a power requirement of 10.2 Watts.

C. OPERATING PARAMETERS

The detector operating temperature is critical to performance and the system is designed for a 40 °C to -40 °C survival range. Optimal temperature is -30 °C with an expected resolution at 662 keV of about 9.6% FWHM at this temperature. The Gamma Ray Spectrometer weighs 6.5 kg with a .36 W power requirement and a 688 bps rate telemetry data requirement.

The orbital period of the spacecraft is 118 minutes, which yields a ground track of about 50 km per 30 second data set. Two sets of data will be returned at each 30 second interval, a BGO spectrum from 01. to 9 MeV in each: i)coincidence and ii) anticoincidence with the plastic shell. The data will be binned into approximately 100 km x 100 km pixels over the lunar surface, in order to determine local variations in composition. As the mission progresses over the course of a year, spectral lines will become identifiable in the data over each lunar map pixel. The polar regions will accumulate data quickly since the spacecraft will be in a polar orbit.

IV. SIMULATION METHOD

As mentioned above, the Gamma Ray Spectrometer instrument will provide global maps of the elemental composition of the surface of the moon. The Gamma Ray Spectrometer will detect the naturally radioactive elements potassium, thorium, and uranium, and will also detect iron, silicon, magnesium, aluminum, oxygen, calcium, and titanium by the gamma rays produced during cosmic ray collisions. A simulated lunar spectrum, based on Apollo data, is shown in Figure 4.1. Notice that peaks at specific energies indicate the presence of certain elements.

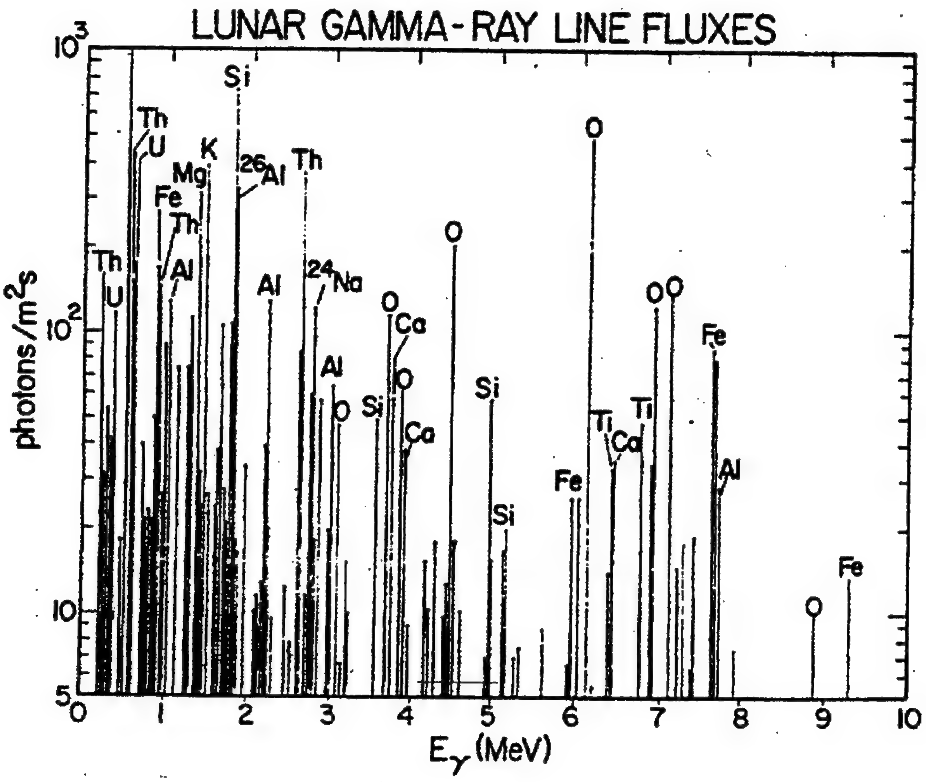

Figure 4.1 Fluxes of lunar gamma rays as a function of energy (Reedy, 1978)

A. SIMULATION PROCESS

A spectrum, appropriate for the Lunar Prospector, can be generated using a process similar to that used for Figure 4.1. The simulation creates a gamma-ray shower

and, using a series of Monte Carlo random number generators, can predict whether a specific gamma ray will interact with the detector, the anticoincidence shield, or neither. The results can then be run through a binning program that simulates the operation of a multi-channel analyzer and stores output from the analog-to-digital converter into separate memory locations. A final spectrum, similar to that shown in Figure 4.1, can then be produced.

1. EGS4

The Electron Gamma Shower Version 4 (EGS4) code is a pre-existing Monte Carlo program which simulates the movement of electrons and photons. It is a general purpose package for the simulation of the coupled transport of electrons and photons in an arbitrary geometry for particles with energies above a few keV up to several TeV (Jenkins, Nelson, and Rindi, 1988). EGS4 is an updated version of EGS3 developed at the Stanford Linear Accelerator Center and introduced in 1978. Version 4 extended the upper and lower energy limits of the previous version. The lower limit extension was forced by the growing number of organizations involved in medical physics and dosimetry research.

EGS4 tracks each and every particle until its energy drops below a lower energy limit or it reaches a geometric boundary. Because of the statistical nature of the Monte Carlo method, the accuracy of the output depends on the number of shower events or cases. These Monte Carlo calculations can be very time consuming so EGS4 breaks the computational tasks into two parts. First, the preprocessor code (PEGS) is used to create media information for all the materials used in the detector system and prepares them in a form for fast numerical evaluation. Then another code (EGS4) uses these data to perform the particle shower simulation.

The EGS4 code consists of two user-called subroutines, HATCH and SHOWER, which call other EGS4 subroutines, which in turn call the user-written subroutines HOWFAR and AUSGAB. HOWFAR specifies the geometries of the spectrometer and thus will determine "how far" a particle travels. AUSGAB, German for output,

determines the scoring or output of the shower. To use EGS4 the user must write a MAIN program and the subroutines HOWFAR and AUSGAB. The user runs the MAIN program which calls the HATCH subroutine that "hatches EGS" by doing an initialization and by reading the data from PEGS for the materials requested. Once this intialization is completed, MAIN calls SHOWER. Each call to SHOWER results in a generation of one case. The arguments to SHOWER specify the parameters of the incident particle initiating the cascade. Figure 4.2 depicts the flow control of the EGS4 program with the dashed line separating existing EGS4 code and user generated code (Jenkins et al., 1998).

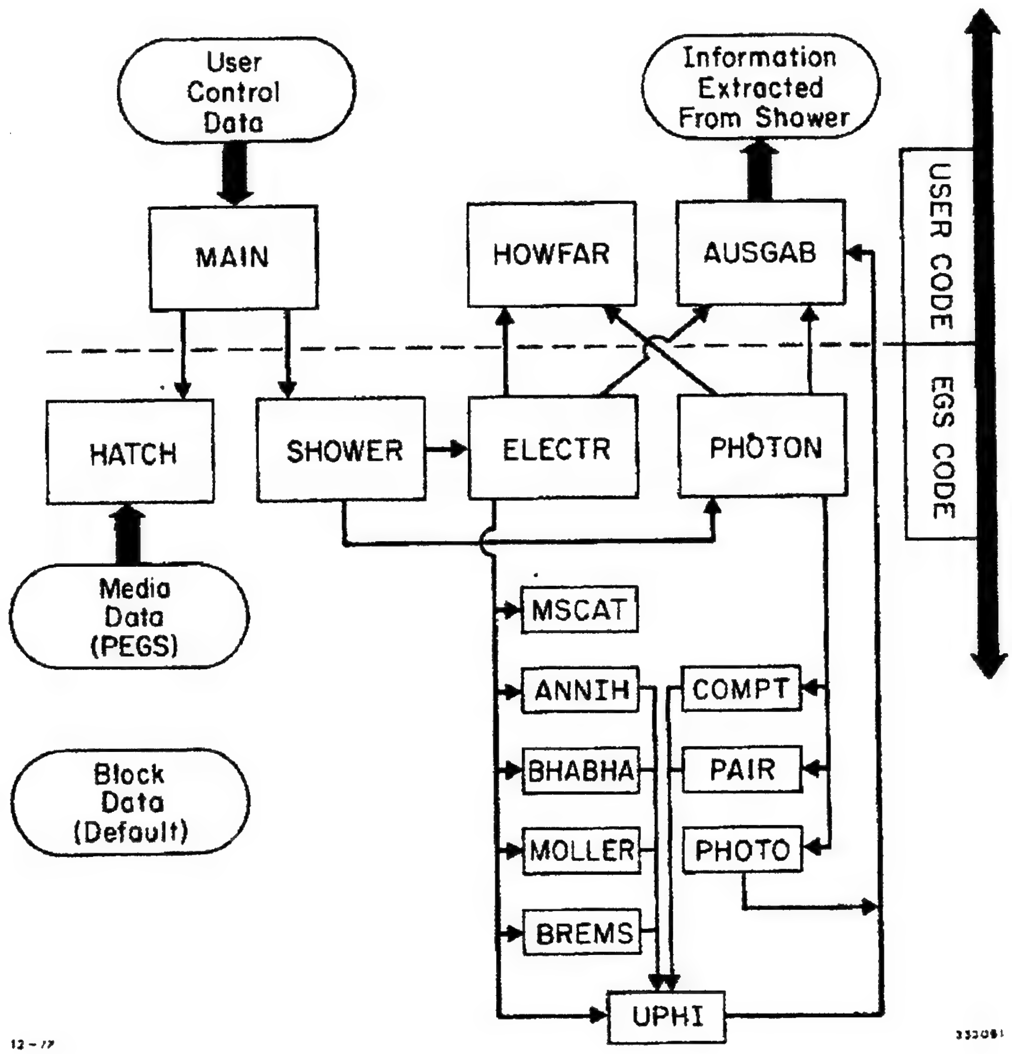

Figure 4.2 Flow control with user using EGS4. (Jenkins et al., 1988)

B. IMPLEMENTATION

A predicted spectrum was created using the EGS4 FORTRAN particle simulation code. The EGS4 code and all the necessary FORTRAN programs to create the user written code were already loaded on a microVAX 3500 computer located at NASA Ames Research Center. Simulations had already been generated for a number of different silicon detectors. Some user-written code and subroutines had to be modified for the BGO detector used aboard the Lunar Prospector.

The PEGS4 program generates the media information and need only be run if materials used in the spectrometer change. Specifications on media information are read in from a user-written file. This file was modified to add BGO and BC454. If the material is a compound, such as BGO and BC454, then the elements involved and their proportions must be specified. For example, BGO was added with a density of 7.13 g/m^3 and a composition of 67.10% bismuth, 17.50% germanium, and 15.4% oxygen.

Before continuing, the MAIN user program, previously named SI-NASA, had to be substantially modified. SI-NASA specified the geometries, initial parameters, and output format for silicon detector simulations. Mr. Steven Zins, programmer at the NASA Ames Research Center, made the necessary modifications for the Lunar Prospector's BGO detector and renamed this program LUNPRO3. Both LUNPRO3.FOR and EGS4.FOR were complied and linked together. A FOR/CHECK=NOOVERFLOW command was used to ensure no overflow in the random number generation process.

To create an entire lunar spectrum the EGS4 code had to be run separately for a series of 90 different gamma ray energies. These energies ranged from 0.197 MeV to 7.724 MeV and were chosen because they were the main lines fitted in the Apollo data. The output from the 90 cases of the shower simulation, in the form of data arrays, were stored in BGO.SAV files. The BGO.SAV files contain data arrays that vary from 10,000 to 100,000 lines in length, each line being a series of energies from each detector region. The 90 BGO.SAV files are weighted and sent through a binning program called BGO-NEW4 to make an output file of 512 channels from 0.1 to 9 MeV, which are the specifications of the Lunar Prospector's multi-channel analyzer. The binned data from the VAX was then downloaded to a Macintosh computer and the Kaliedagraph software application program was used to create a plot or graph of counts versus energy.

V. SIMULATION DATA, RESULTS, AND ANALYSIS

Monte Carlo simulations, using the EGS4 code, were performed to get an indication of the data to be returned by the Lunar Prospector's Gamma Ray Spectrometer instrument. These predictions will be used as a comparison for the actual data, in order to determine how well the spectrometer is working. The simulation is a prediction of the Gamma Ray Spectrometer instrument response in lunar orbit, using 90 spectral lines and a continuum gamma ray background taken from Apollo 15 and 16 data. The Monte Carlo program used the exact dimensions and composition of the Gamma Ray Spectrometer in order to most accurately predict spectral performance, assuming an operating temperature on orbit of -30 °C. The simulation output shows the spectrum from both interactions in the BGO (accepted) and the plastic shell (rejected) in an attempt to portray the actual data returned from Lunar Prospector. As mentioned in Chapter II, there is information to be gained by obtaining both of these data sets. In principle the accepted spectrum is the cleanest, since all the incident gamma ray energy is deposited entirely in the BGO. There is important information in the rejected (coincidence) spectrum which can be used to good advantage. The rejected data consists of gamma rays that had all or part of their energy deposited in the plastic shell and part of their energy deposited in the BGO. This scattering process mimics the Compton scattering of the spectral emission lines by the lunar surface before the gamma rays reach the Lunar Prospector spacecraft, and so are similar to the continuum background spectrum which rides below the line spectrum. As such, a properly scaled version of the rejected spectrum can be subtracted from the accepted anticoincidence spectrum to reduce continuum background from the lunar surface. Figure 5.1 shows the Gamma Ray Spectrometer's simulated response to a 2.741 MeV gamma ray and depicts the accepted, rejected and total spectra for a single line. The total is the sum of the accepted and the rejected.

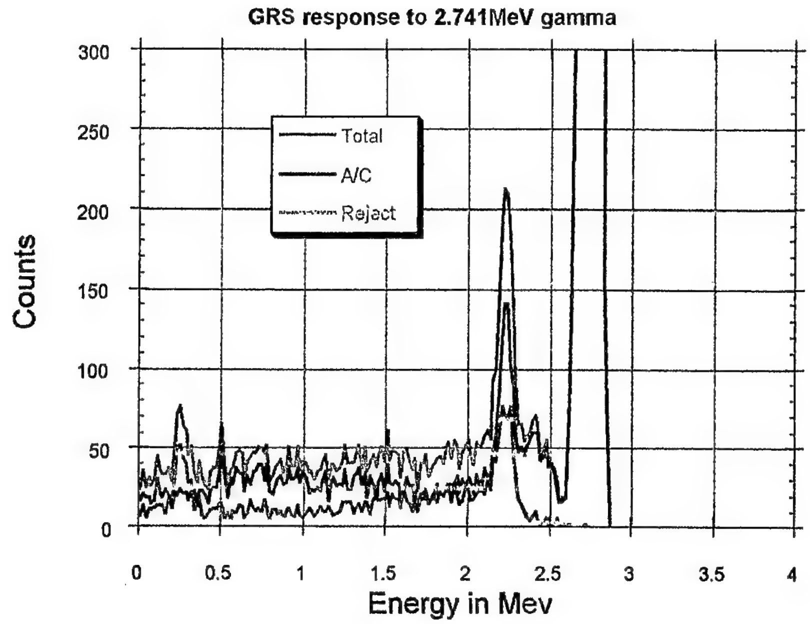

Figure 5.1 Example accepted and rejected spectra for a 2.741 MeV gamma ray

Notice the peak at 2.741 MeV, which is actually cut off to show the details of the low energy tail. Notice the lowest curve (or the rejected spectrum) could be subtracted from the accepted spectrum to lower the continuum background.

Although it is not necessary to examine the output for each of the 90 energies used to generate the Gamma Ray Spectrometer's lunar spectrum, it is interesting to look at a plot of energies from the two extremes. Figure 5.2 shows a plot of the accepted spectrum for a 0.197 MeV gamma ray. Notice how clean the peak is at 0.197 MeV due to the fact that photoelectric absorption dominates at this low energy. Recall that photoelectric absorption is an excellent way to measure the original gamma ray energy because a single peak appears at the same total electron energy as the incident gamma ray.

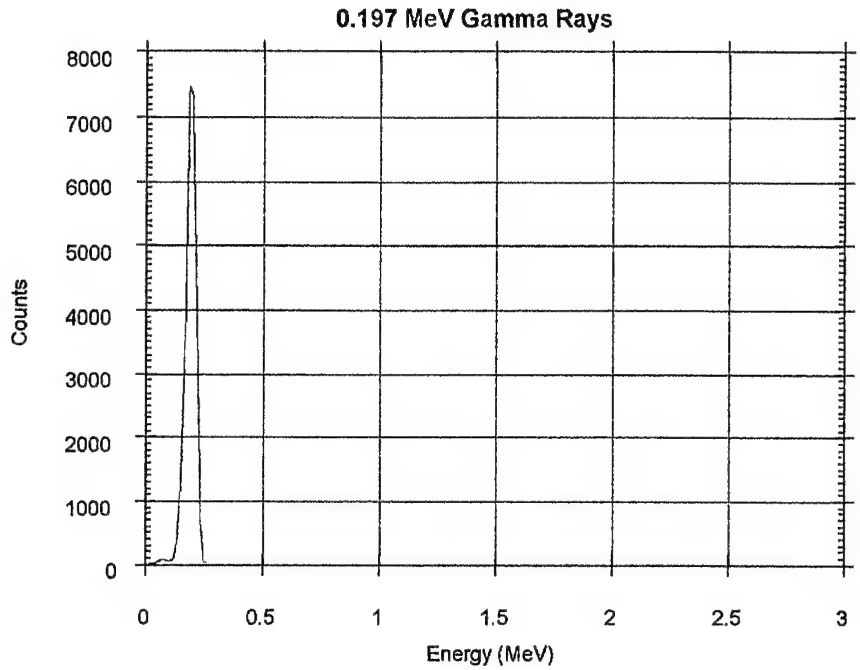

Figure 5.2 The accepted spectrum for a 0.197 MeV gamma ray

Figure 5.3 below shows the accepted spectrum for a 7.724 MeV gamma ray. Recall that pair production dominates at higher energies and that the double escape peak normally falls at 0.511 or 1.022 MeV below the full energy peak. The full energy peak is clearly evident at 7.724 MeV and a secondary peak appears near the energy of the expected single escape peak at 7.213 MeV.

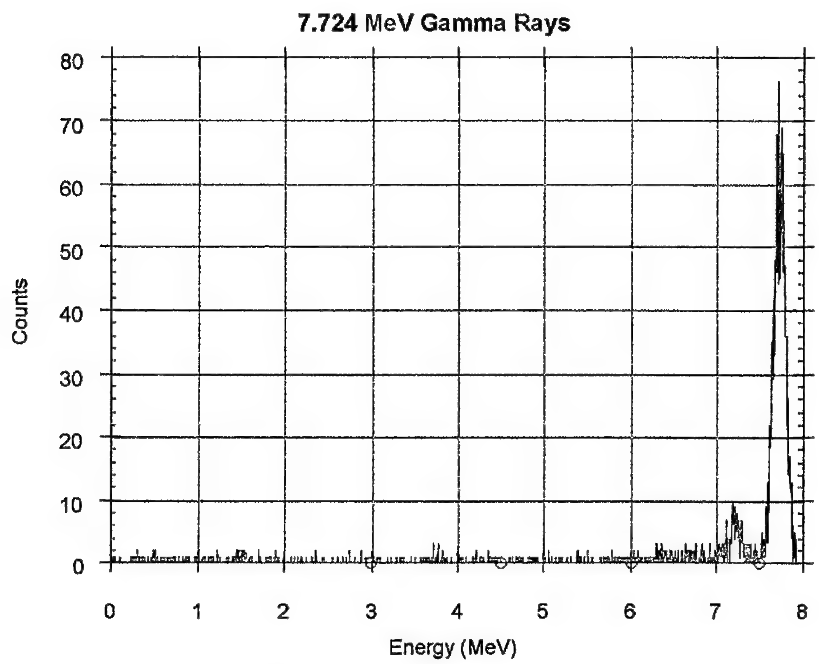

Figure 5.3 Accepted Spectrum for a 7.724 MeV gamma ray

After combining the weighted output from all 90 lines and running them through the binning program, a full predicted lunar spectrum for the Gamma Ray Spectrometer was created. The energies were broken down and binned into the Gamma Ray Spectrometer's 512 available channels, which are depicted along the x-axis of Figure 5.4. Each channel has the width of 17.578 KeV because the 9 MeV range was divided by 512 channels. The peaks at various channels also coincide with peaks at their associated energy. A comparison of Figure 5.4 to Figure 4.1 (note Figure 4.1 is a log scale) shows clear similarities. Starting from right to left, the following elements can be identified. The peak at channel 444 (7.8 MeV) indicates the presence of iron. The next double peak

at channel 398 (7.0 MeV) indicates oxygen. The next two large peaks and the double peak at channels 352,260, and 224 respectively also indicate oxygen. The peak which measures just above 200 counts at channel 148 (2.6 MeV) indicates Thorium. Aluminum gives a small reading of just over 100 counts at channel 129 (2.3 MeV). Silicon has the strongest reading on the graph, as indicated by the large peak at channel 104 (1.8 MeV). The peaks to left of the large Silicon peak indicate potassium, magnesium, iron, uranium, uranium, and thorium respectively.

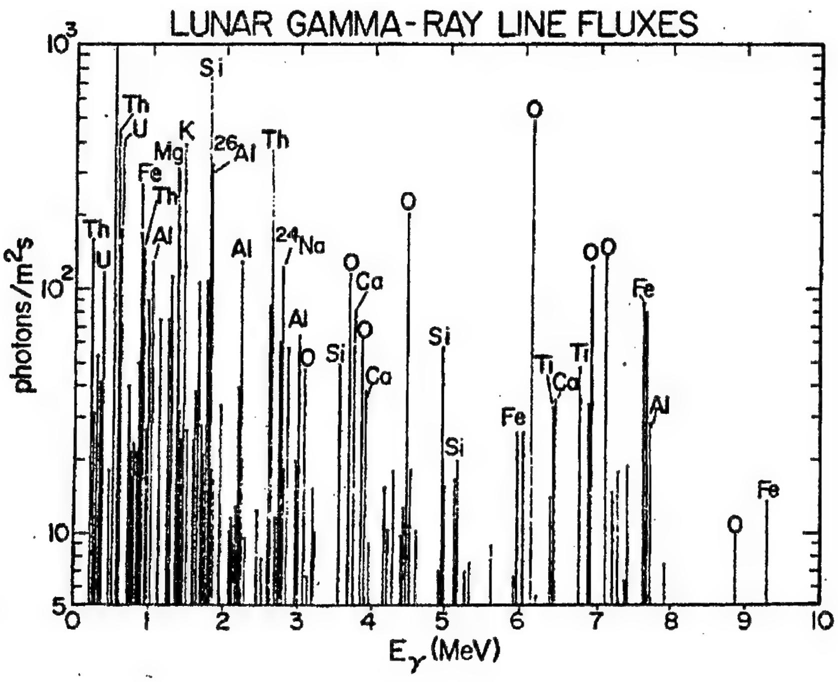

Figure 4.1 Fluxes of lunar gamma rays as a function of energy (Reedy, 1978).

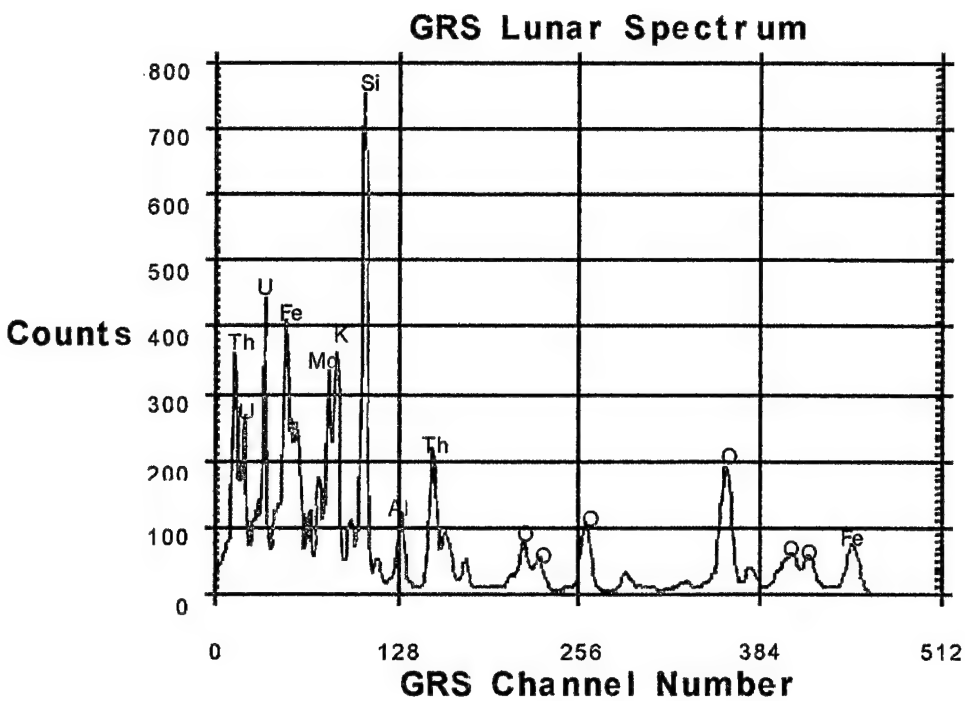

Figure 5.4 Full predicted lunar spectrum for the Gamma Ray Spectrometer depicting all 90 lines.

VI. CONCLUSIONS AND RECOMMENDATIONS

The expected response of the Gamma Ray Spectrometer instrument was determined using a Monte Carlo simulation. The full lunar spectrum was generated using 90 lines and a continuum background taken from Apollo 15 and 16 data. These predictions will be used as a comparison for the actual data, in order to determine how well the spectrometer is working. The data returned from Lunar Prospector can also be compared to the equatorial data from Apollo 15 and 16. The Monte Carlo simulations are based on Apollo data and can predict only averaged data. Some variations are expected, possibly in the poles, since only Apollo equatorial data is available at this time.

The exact dimensions and composition of the Gamma Ray Spectrometer were entered into the Monte Carlo program to most accurately predict spectral performance. The program accounted for the geometry of the detector and the anticoincidence shield. The limitation of this exercise, however, is that the program only allowed for the gamma ray to be a point source located directly underneath the detector. The actual detector, on Lunar Prospector which is not spin-stabilized, won't continuously point toward the lunar surface. Instead, the detector will remain fixed while the Lunar Prospector orbits the moon. Therefore, the source (or lunar surface) will move from under the detector, to the side, to the top, and then to the opposite side of the detector as the Lunar Prospector orbits. Future recommended study could include moving the point source to various locations surrounding the detector.

The study of Radiation Detection and Gamma Ray Spectroscopy is an extremely complex and specialized field and some may wonder what application it has for a military officer. The study of the electromagnetic spectrum, even a very small portion of it, has great applications for an Army Signal officer. A Signal officer must be a master of the entire realm of communications, to include telephone, radio, microwave, satellite, computer, and video. A solid understanding of a portion of the electromagnetic spectrum can give a Signal officer the background needed to survive in today's fast-paced world of ever-changing technology.

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